Feasibility of Geophysical Monitoring of Carbon-Sequestrated Deep Saline Aquifers

Project: DE-FE0001160

Collaborative Review

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Project Team

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  - WesternGeco (Schlumberger)
- DOE (NETL) Project Manager
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Agenda

- Importance
- General overview
  - Available tools
    - Seismic
    - Flow simulation
- Project objectives
- Project Phases
- Project Status
- Conclusions
- Acknowledgements

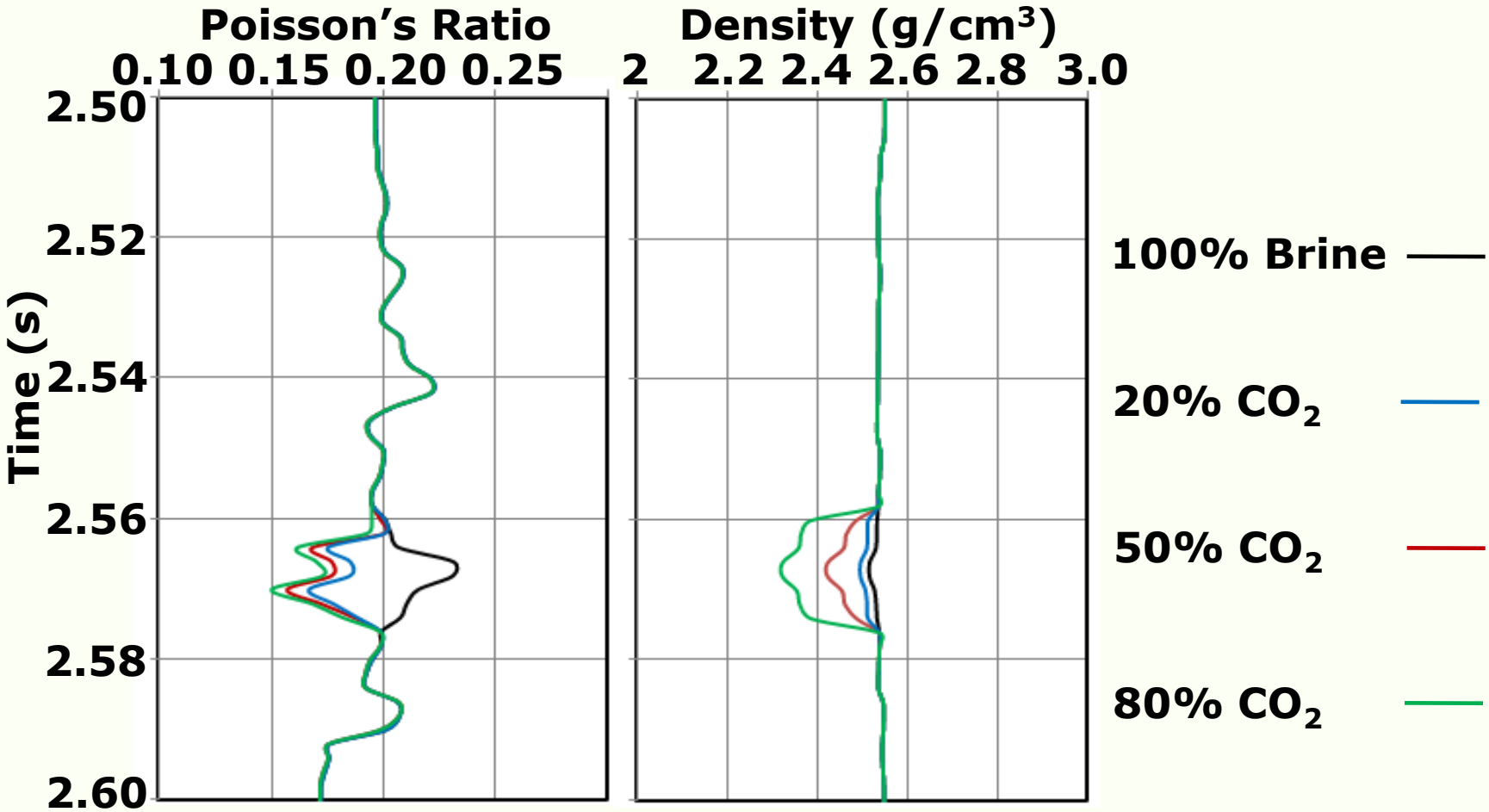
Importance

- **Monitoring Verification and Accounting (MVA)**
  - One of the important aspects of carbon sequestration
    - Allows verifying if the sequestrated gas is in place
    - Does not disturb the integrity of surrounding rocks
- **For accuracy**
  - Available Geophysical tools must be calibrated with flow simulation models
    - Will allow if we can monitor and account for the injected CO_2 during the post-injection scenarios.

General Overview

- **Available geophysical monitoring tools**
  - Microgravity
  - Electromagnetic (EM)
  - Seismic
- **Microgravity**
  - Sensitive to the variations in density
  - Worked well in relatively shallow formations
  - May not be suitable for our purpose
- **EM**
  - Sensitive to the variations in resistivity
  - May/may not be suitable for the depths of our interest
- **Seismic**
  - Well accepted and well developed technology
  - Most suitable for our purpose
- **Here we will look at combining seismic with flow simulation**

General Overview- Seismic



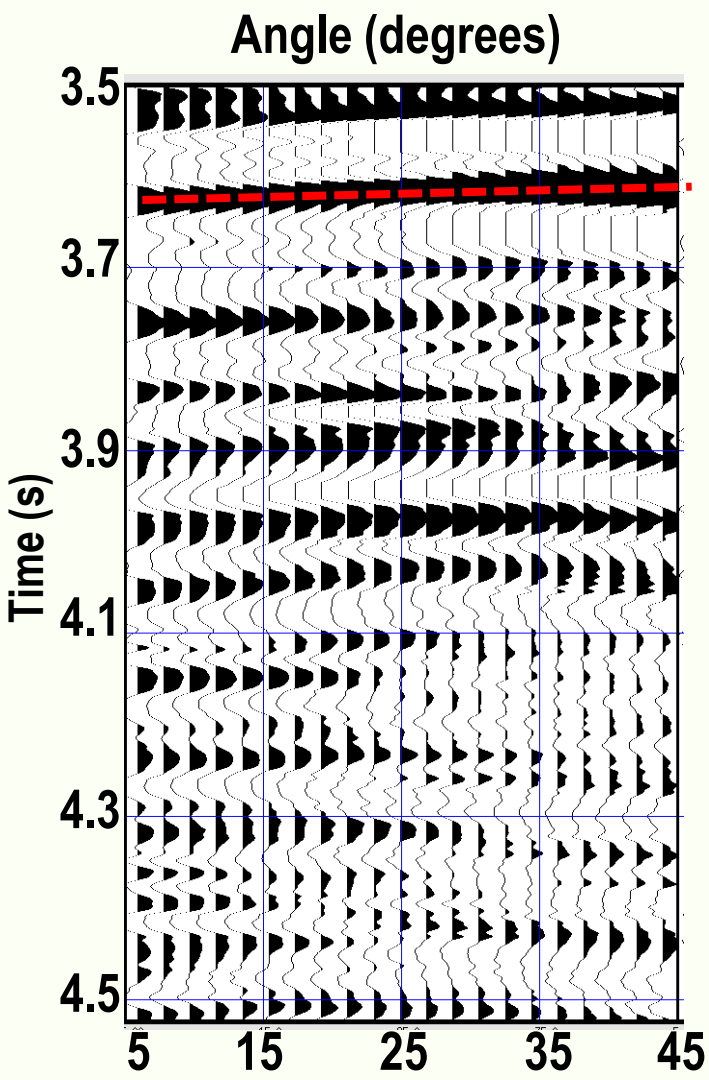
Density is more sensitive to CO_2 than Poisson's ratio

How can we accurately predict density?

General overview (seismic)

- Generally P-wave (vertical component/Pressure) seismic data are used in reservoir characterization
  - Relatively inexpensive
  - We know how to interpret it
- Is P-wave seismic data sufficient to obtain density information?
- Let's first look at Amplitude Variation with Offset/Angle (AVO/AVA) methods.

AVO/AVA-based methods



$$R_{PP} \approx \underbrace{\frac{1}{2}\left(\frac{\Delta V_P}{V_P}+\frac{\Delta \rho}{\rho}\right)}_{A}+\underbrace{\left(\frac{1}{2}\frac{\Delta V_P}{V_P}-\frac{2\Delta \mu}{\rho V_P^2}\right)}_{B}\sin^2\theta+\underbrace{\frac{1}{2}\frac{\Delta V_P}{V_P}}_{C}\sin^2\theta\tan^2\theta$$

$$\begin{pmatrix} d_1 \\ d_2 \\ . \\ . \\ d_n \end{pmatrix} = \begin{pmatrix} 1 & \sin^2\theta_1 & \sin^2\theta_1\tan^2\theta_1 \\ 1 & \sin^2\theta_2 & \sin^2\theta_2\tan^2\theta_2 \\ . & . & . \\ . & . & . \\ 1 & \sin^2\theta_n & \sin\theta_n\tan^2\theta_n \end{pmatrix} \begin{pmatrix} A \\ B \\ C \end{pmatrix}$$

d **G** **m**

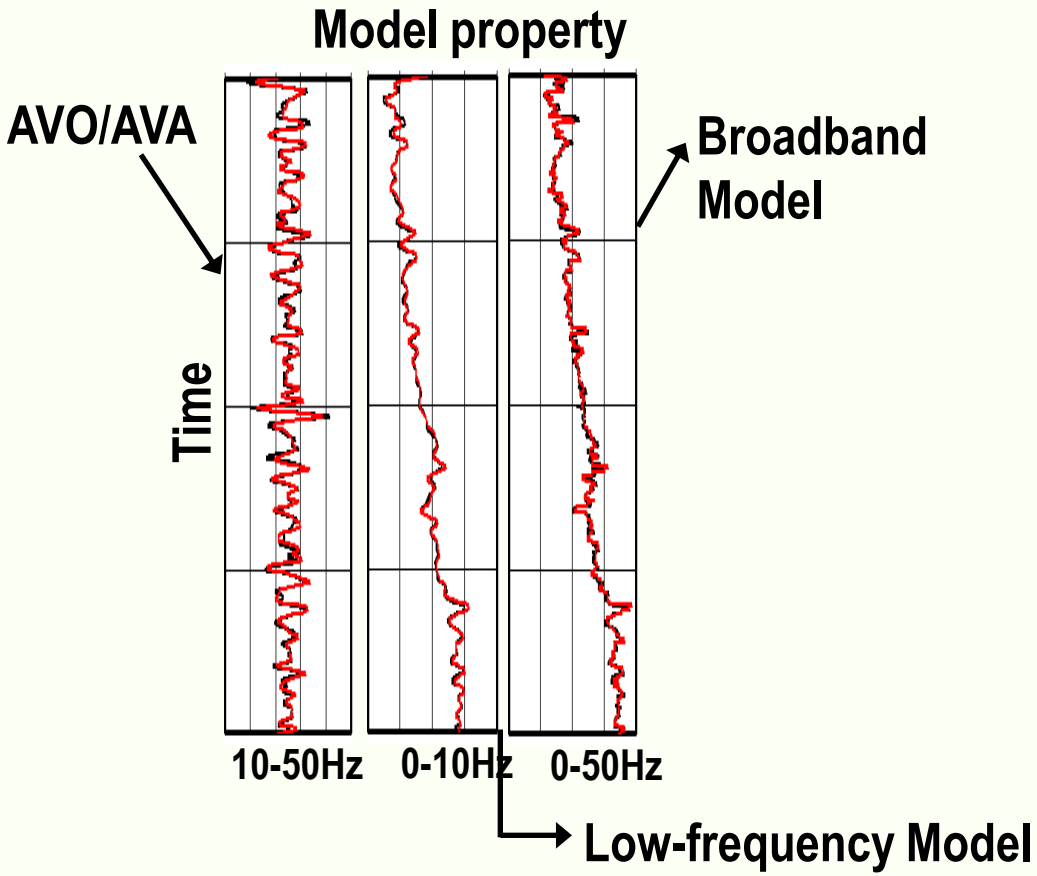
$$\mathbf{m}^{est} = \left[\mathbf{G}^T\mathbf{G}\right]^{-1}\mathbf{G}^T\mathbf{d}$$ (Least Square)

$$\mathbf{m}^{est} = \left[\mathbf{G}^T\mathbf{G}+\varepsilon^2\mathbf{I}\right]^{-1}\mathbf{G}^T\mathbf{d}$$ (Damped least Square)

Assumptions in AVO/AVA

Assumption-1 → AVO/AVA provides narrow band model

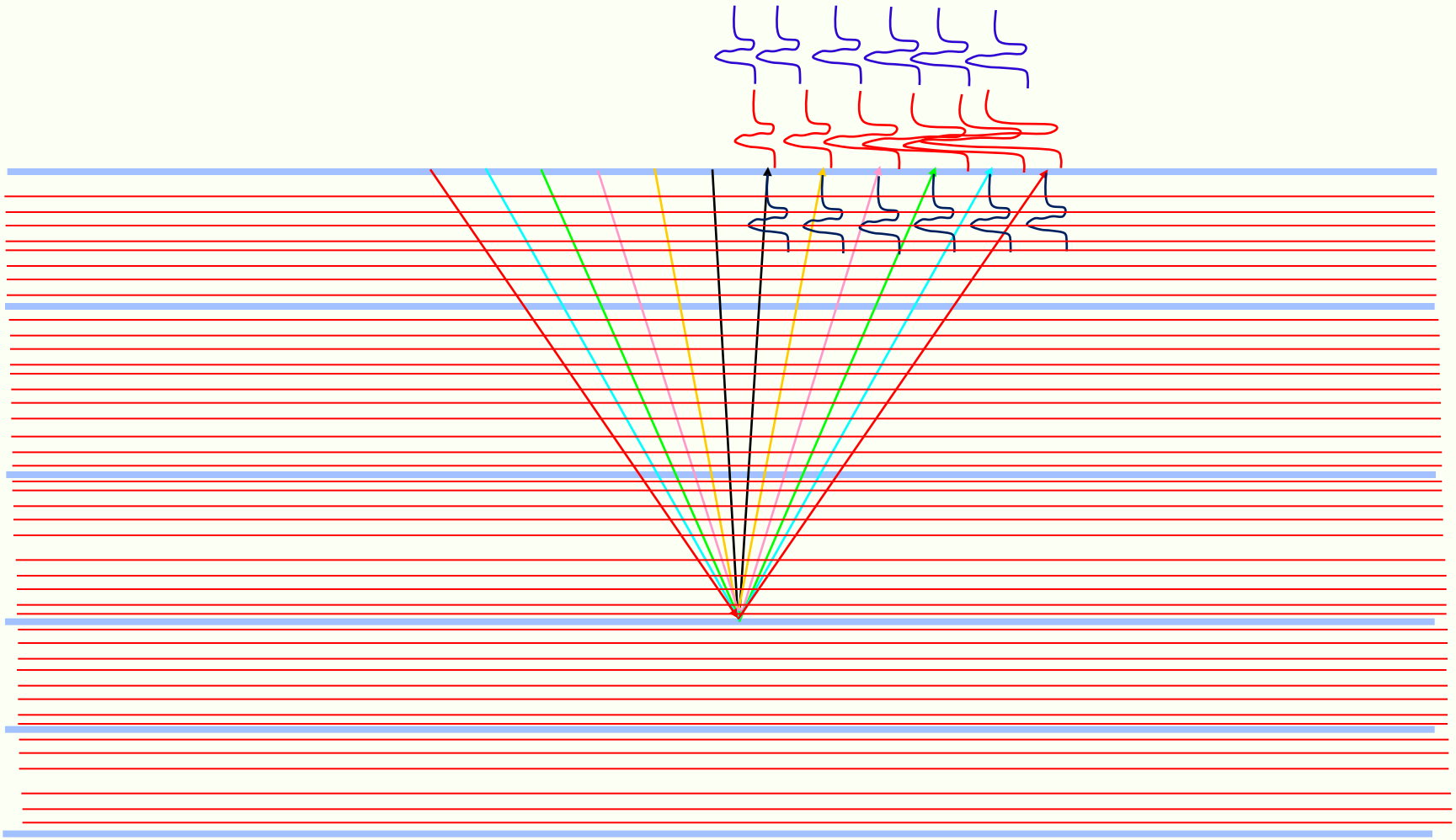
- Provides P-, S- velocity and density contrasts
  - High-frequency model
- To get the broadband model, low frequency model information must be provided
- Broadband model is required for lithology and fluid prediction



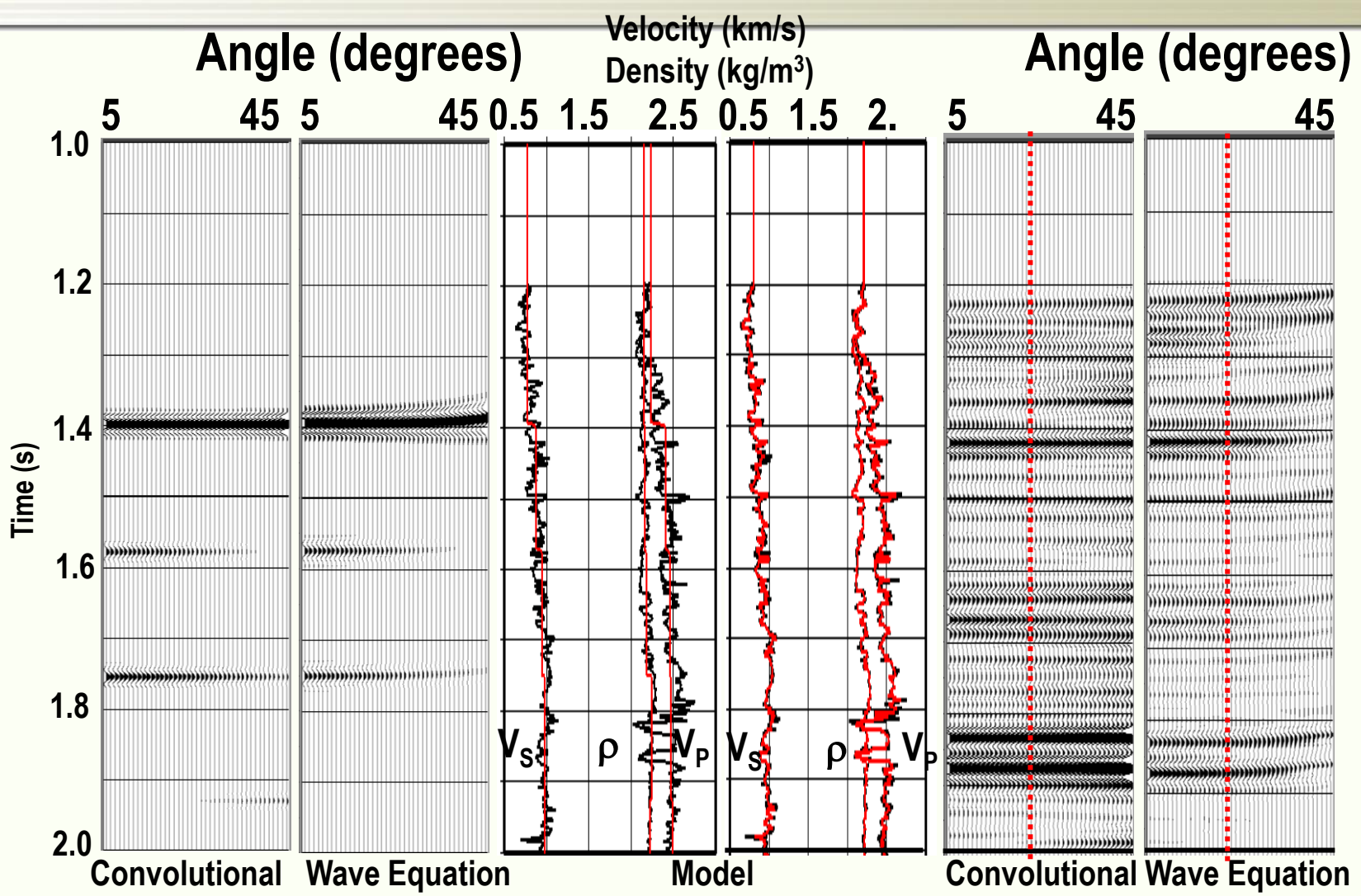
Assumptions in AVO/AVA

Assumption 2 → Fundamental Assumption

- Prestack reflection amplitudes:
  - Proportional to the plane P-P and/or P-S reflection coefficients
- Convolutional modeling assumption:
  - Primary (mode-converted) reflections.
  - No transmission loss.
  - No other wave propagation effects.



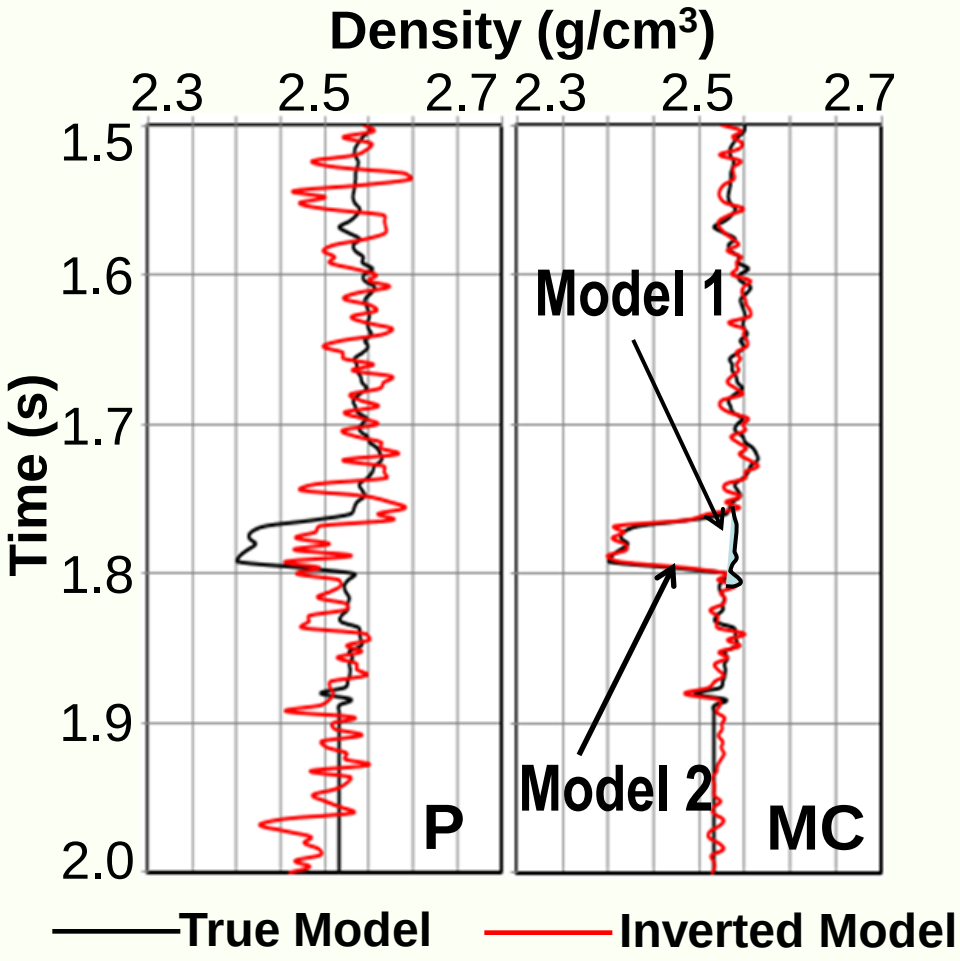
Wave Interference effects do not allow AVO/AVA to give optimum results.


Angle (degrees)
Velocity (km/s)
Density (kg/m3)
Angle (degrees)
5
45
5
45
0.5
1.5
2.5
0.5
1.5
2.
5
45
45
1.0
1.2
1.4
1.6
1.8
2.0
Time (s)
VS
ρ
VP
VS
ρ
VP
Convolutional
Wave Equation
Model
Convolutional
Wave Equation

The correct approach

- Use a methodology that handles all these wave propagation effects:
  - Primary and mode-converted reflections
  - Inter-bed multiples
  - Transmission loss
  - Ray-bending
  - ……..
- Step beyond conventional AVO
  - Prestack waveform inversion (PWI)

General Overview- Seismic



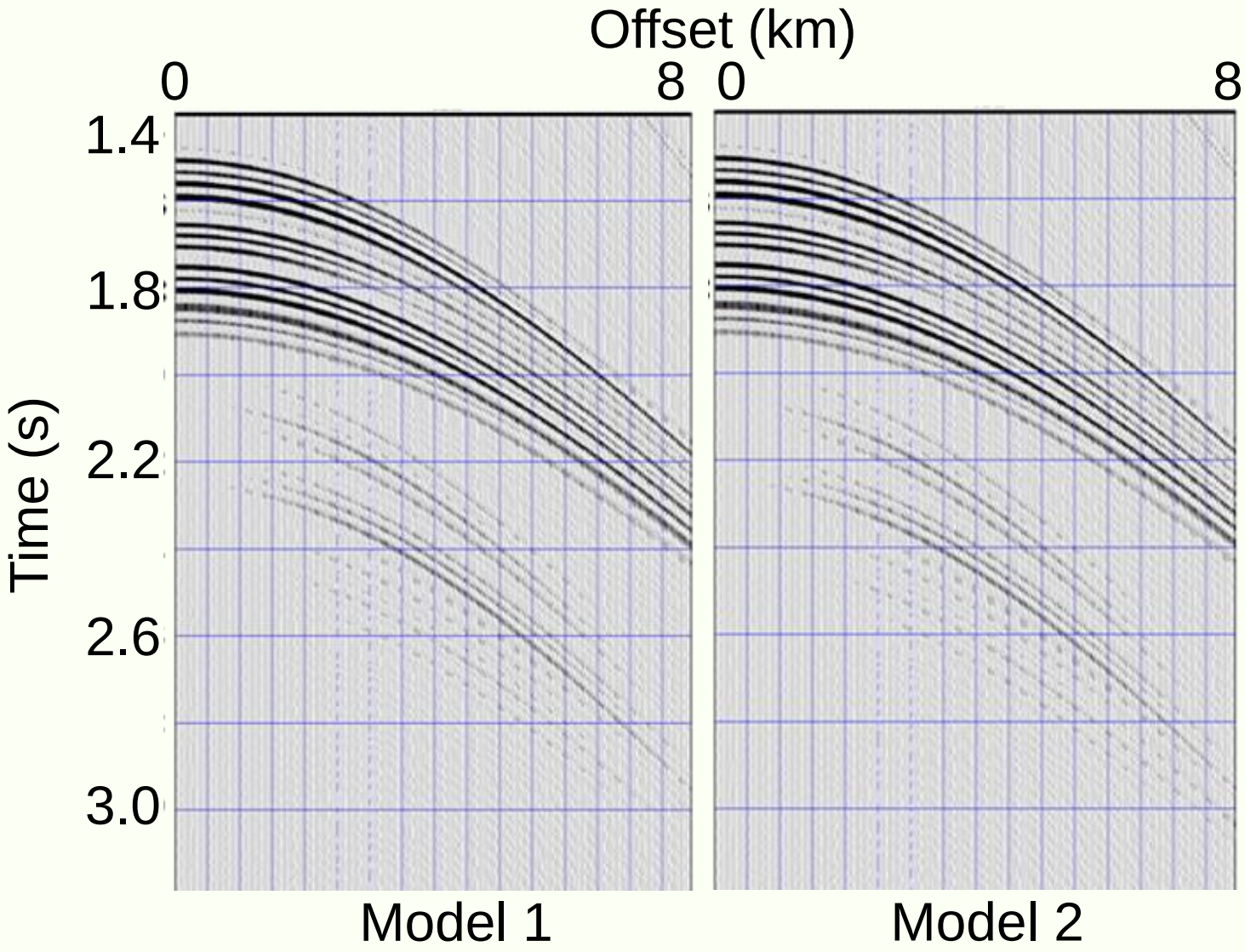
Density is more accurately predicted in Multicomponent inversion than P-wave only inversion.

Multicomponent seismic data are required for monitoring.

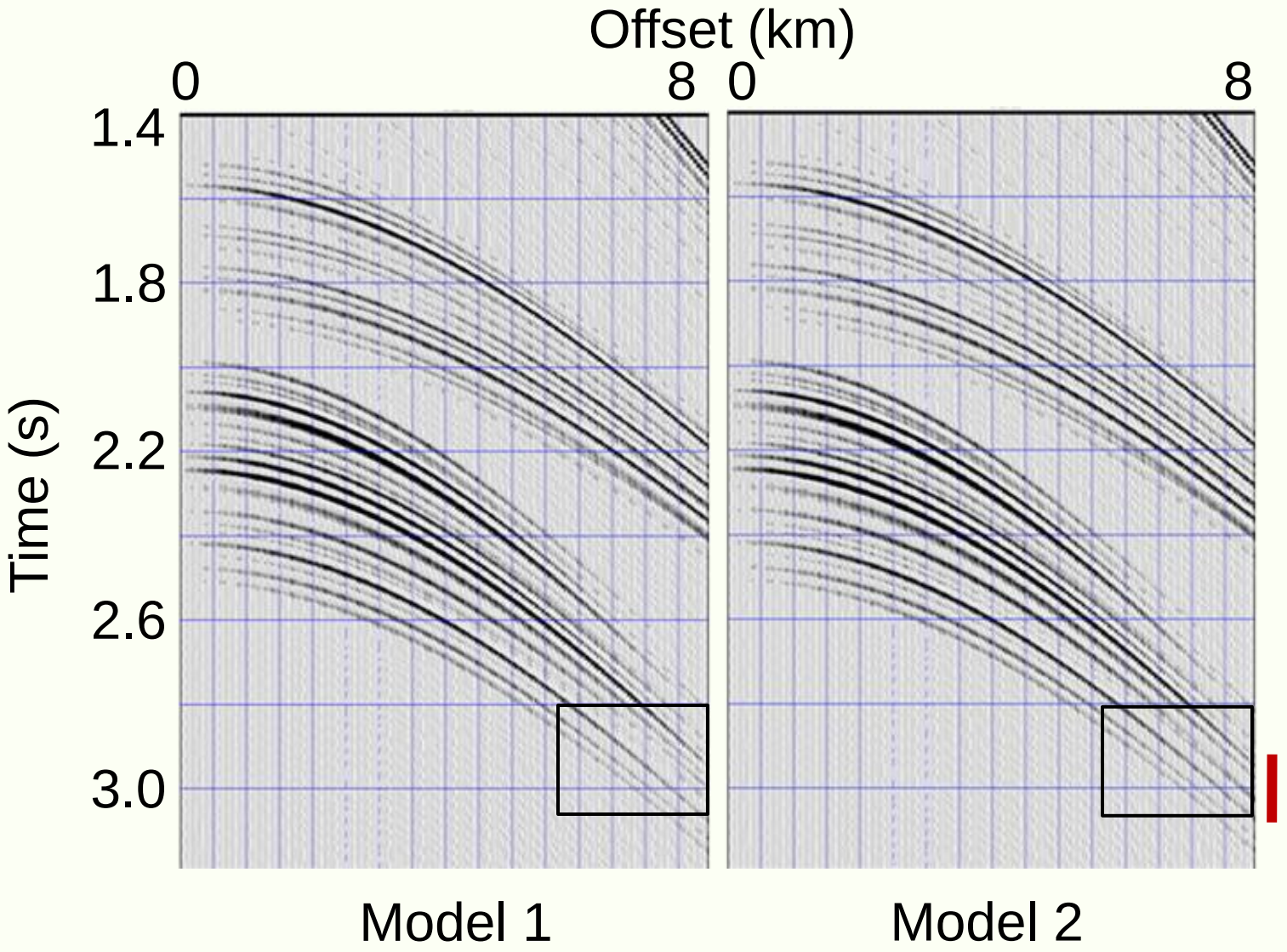
Why multi-component data is sensitive to density?

Follows from the fundamentals of seismic wave propagation

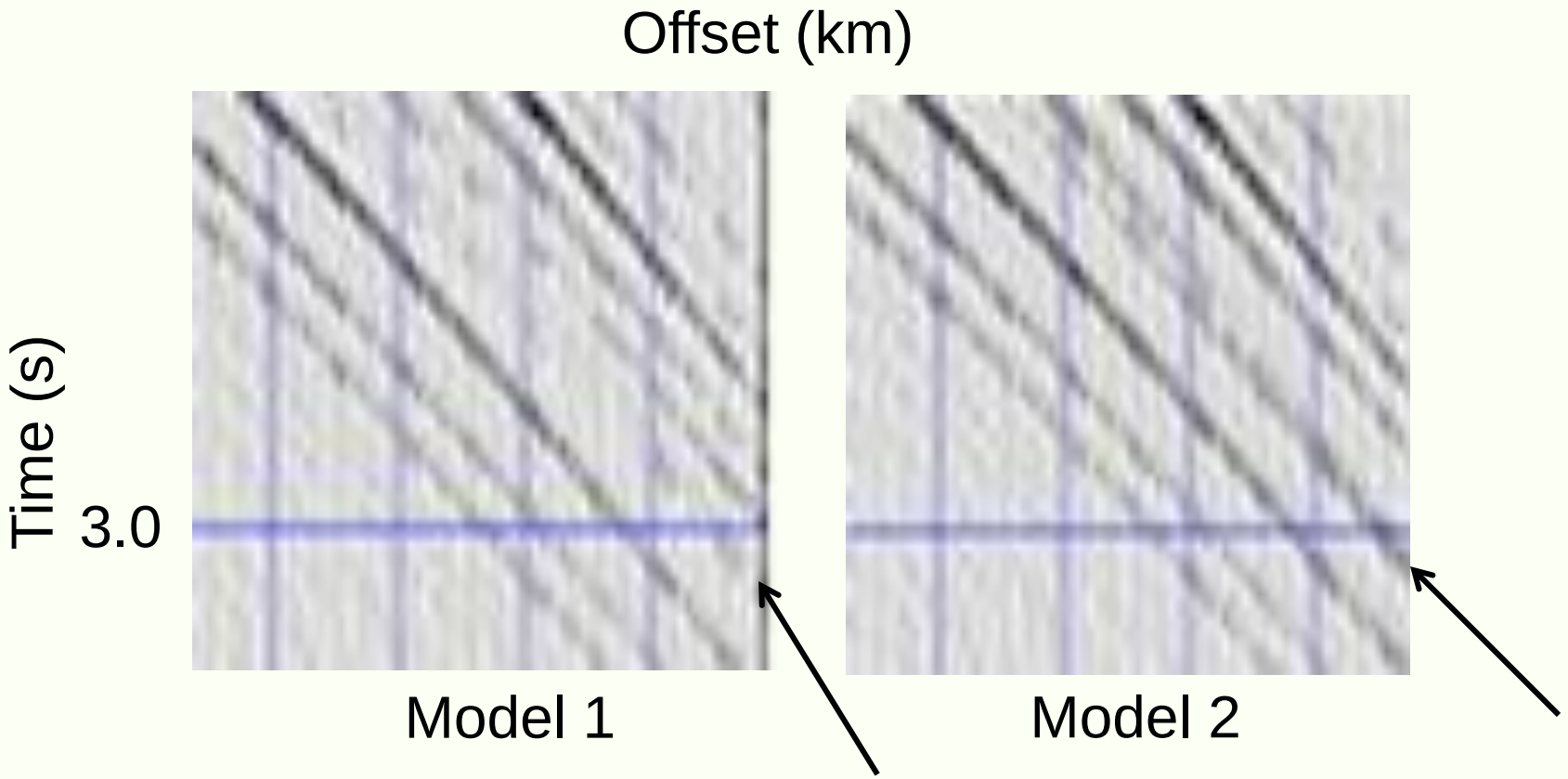
Vertical Component



Horizontal (Radial) Component



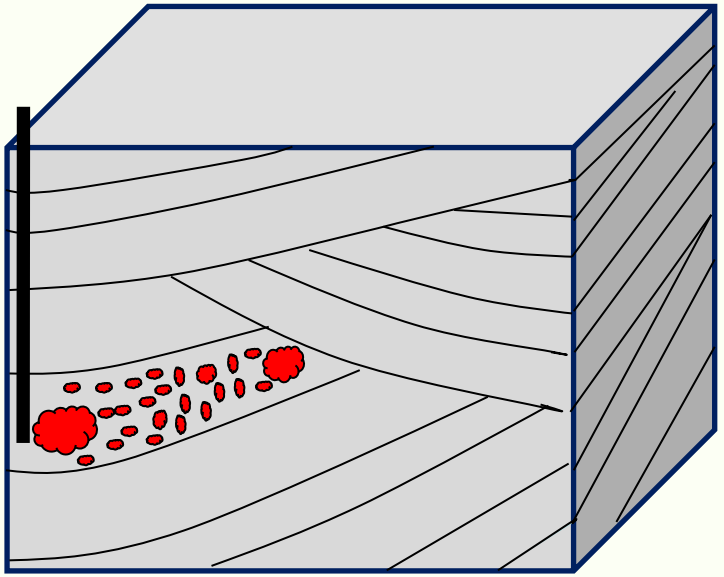
Horizontal (Radial) Component



This difference in the radial component response is the key to an accurate extraction of density from multi-component seismic data

General Overview- Flow simulation

- **Post-injection scenario**
  - Injected CO_2 bubble forms a patchy saturation
    - Controlled by rewetting and trapping of CO_2 by bypassing and snap-off mechanisms
  - Accurate prediction requires
    - Experiment with core samples to incorporate the hysteresis of capillary pressure and relative permeabilities into simulation models
    - Combine simulation models with seismic to study if such post-injection patchy models could be monitored and accounted for



Project Objective

- **Develop a realistic 3-D model**
- **Perform multi-phase flow simulation**
  - Include hysteresis of capillary pressure and relative permeabilities
- **Develop seismic waveform inversion**
  - Multicomponent
- **Combine flow simulation with waveform inversion**
  - if seismic waveform inversion can accurately predict CO_2 plume movements within storage aquifers in post-injection scenarios involving rewetting and trapping of CO_2 by bypassing and snap-off mechanisms

General Overview- required workflow

- **Generation of a 3-D model**
  - Must be realistic
    - Based on Well and seismic data
  - Based on data availability, Moxa-Arch and/or Rock-Springs uplift are the ideal candidates
- **Flow simulation and 3D synthetic seismograms**
  - Use core samples and run saturation experiments
    - Based on the availability of core samples, Moxa-Arch and/or Rock-Springs uplift are ideal candidates.
  - Incorporate experimental results into simulation
  - Inject CO_2 at some representative saline aquifer formations in the original model
  - Run flow simulation to output two/three post-injection models
  - Compute 3-D synthetic seismograms

Phase-1

General Overview- required workflow

- **Prestack waveform inversion**
  - Waveform based inversion of multicomponent seismic data
    - Will include full wavefield response
      - Primary reflections
      - Mode-converted reflections
      - Mode-converted multiples, etc.
- **Calibration of inversion with Flow simulation models**
  - Most crucial component of our investigation
  - Will allow seismic waveform inversion to predict post-injection patchy saturation distribution within aquifer volumes
  - Will involve coordination of expertise between Geology/Geophysics and Petroleum Engineering

Phase-2

General Overview- required workflow

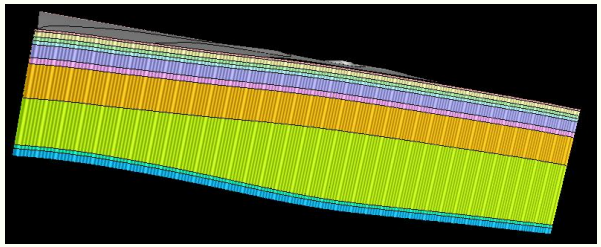
- **Processing of 3-D multicomponent seismic data**
  - Original (baseline) data
  - Post-injection (time-lapse) data
  - Will use Omega-2 processing Software with consulting support from WesternGeco
- **3-D prestack waveform inversion**
  - Inversion of 3-D baseline and time-lapse data volumes
  - Calibration of inverted models with flow-simulation models
  - Prediction of the patchy CO_2 saturation distribution from inversion
- **Project completion**
  - Finalize the project report
  - Transfer the technology to the real sequestration sites

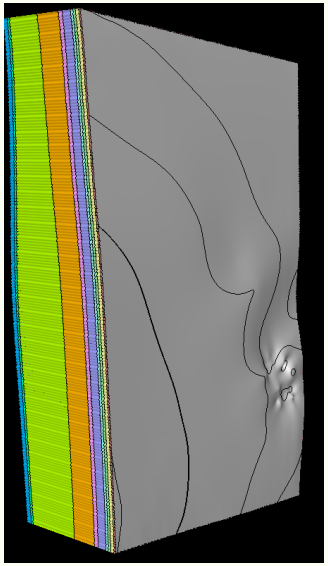
Phase-3

Project Status- Phase-1

3-D model generation, sequestration and flow simulation, and computation of 3-D seismic responses

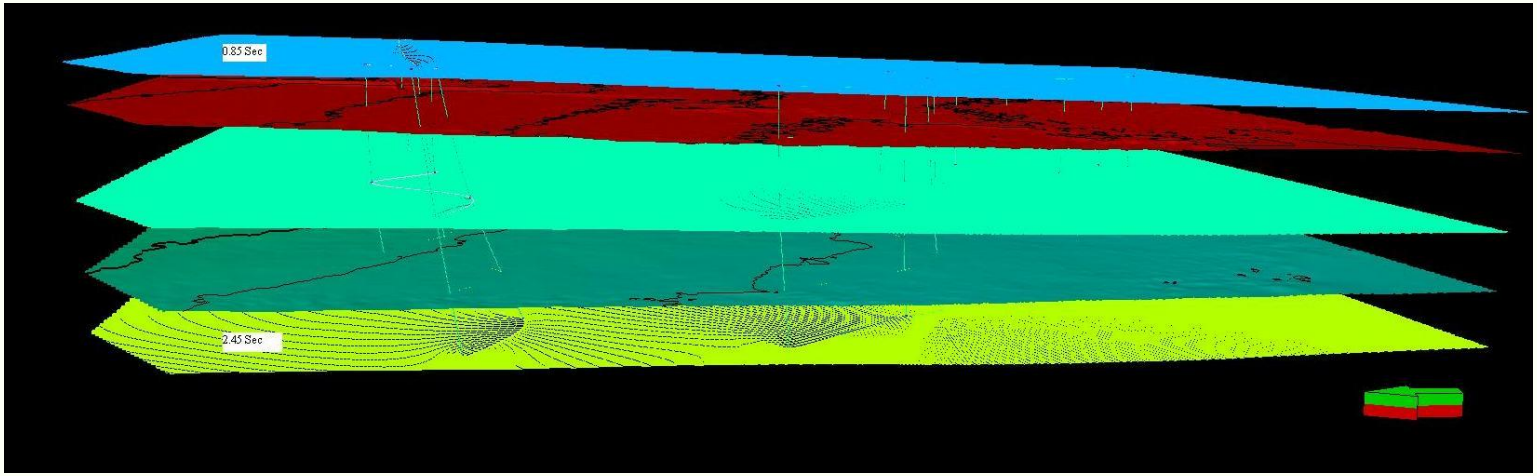
- **Preliminary 3-D Model using Well-data:**
  - Completed
- **3-D Seismic data**
  - PSTM processing completed
- **Final 3-D Model**
  - Nearing completion

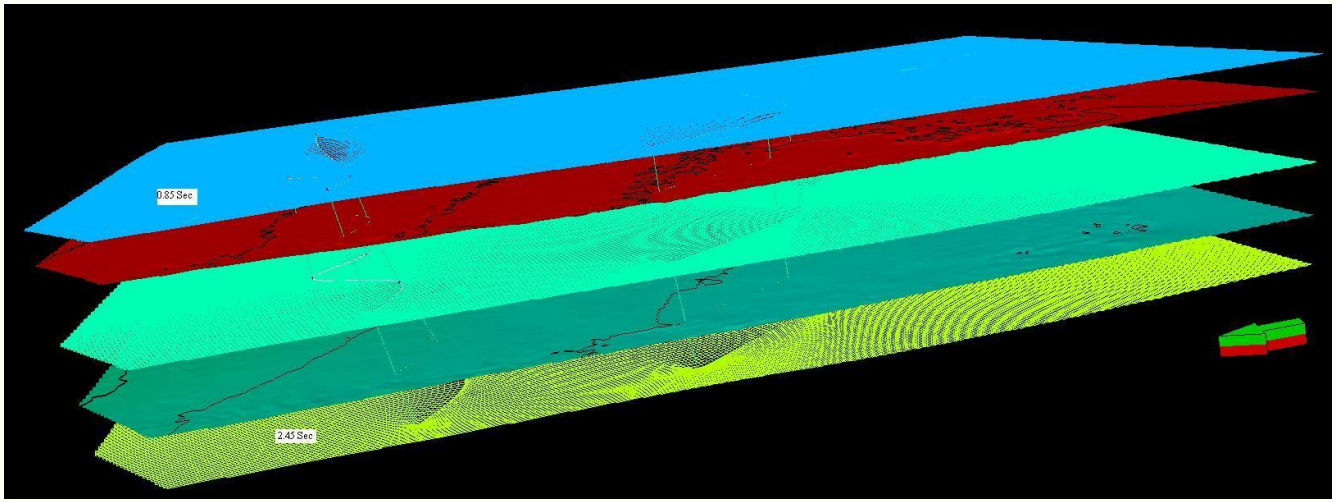




Courtesy Petrel Software (Schlumberger)

Detailed model



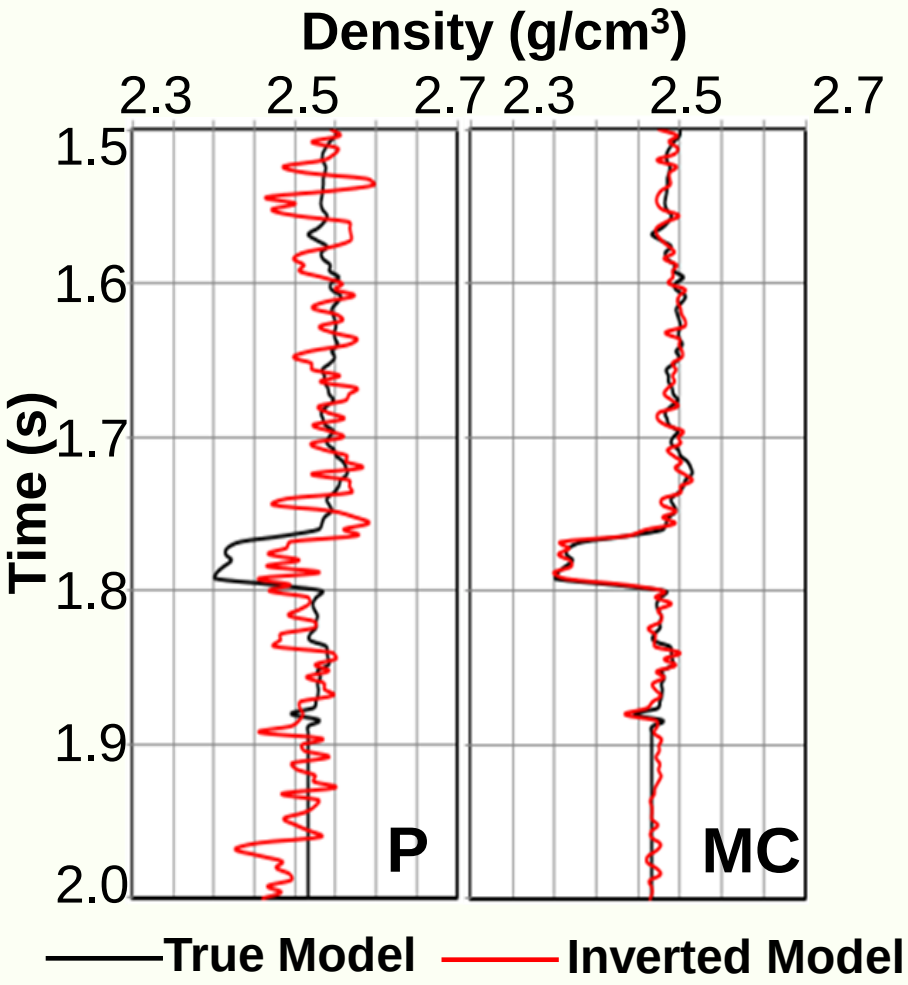


Courtesy Petrel Software (Schlumberger)

Project Status Phase-2

- **Already under development**
  - Major effort of this project
  - Inversion at single location
    - Developed
  - Calibration with flow simulation
    - Will start soon the flow simulations are completed
  - Inversion at multiple locations
    - Being developed

Development of 3-D prestack multicomponent seismic waveform inversion



Conclusion

- **Project description**
  - Objective
  - Importance
- **General Overview**
  - Seismic Aspects
  - Simulation Aspects
    - Definition and description of various tasks and subtasks
- **Projected Timeline**
  - Three years

Acknowledgements

- We sincerely thank DOE/NETL for giving us an opportunity to carry out this research.

Thank You